

Does the galaxy correlation length increase with the sample depth?

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ABSTRACT

We have analyzed the behavior of the correlation length, r_0 , as a function of the sample depth by extracting from the CfA2 redshift survey volume-limited samples out to increasing distances. For a fractal distribution, the value of r_0 would increase with the volume occupied by the sample. We find no linear increase for the CfA2 samples of the sort that would be expected if the Universe preserved its small scale fractal character out to the distances considered (60–100 h^{-1} Mpc). The results instead show a roughly constant value for r_0 as a function of the size of the sample, with small fluctuations due to local inhomogeneities and luminosity segregation. Thus the fractal picture can safely be discarded.

Subject headings: methods: statistical; galaxies: clustering; large-scale structure of Universe

1. Introduction

In recent years, the question of whether the Universe becomes homogeneous on large scales or continues to exhibit fractal structure has been much debated, with different analyses of several three-dimensional surveys of galaxies yielding opposite results (Davis 1997; Pietronero et al. 1997; Guzzo 1997; Cappi et al. 1998; Scaramella et al. 1998; Joyce et al. 1999; Peebles 1998; Wu et al. 1999; Martínez 1999). The standard tool for analysis of clustering in galaxy catalogs is the two-point correlation function $\xi(r)$ (Peebles 1980), which is found to follow reasonably well a power-law $\xi(r) = (r_0/r)^\gamma$ at small separations, $r < 10 h^{-1}$ Mpc. The correlation length r_0 is, therefore, the scale at which the correlation function $\xi(r)$ passes through unity. At a distance r_0 from an arbitrarily chosen

galaxy, the number density of galaxies is on average twice the mean. A strong prediction of the fractal interpretation of galaxy clustering is an increase of the correlation length with the radius of the sample R_s (Pietronero 1987; Guzzo 1997; Sylos-Labini, Montuori, & Pietronero 1998).

$$r_0 = \left(\frac{3 - \gamma}{6} \right)^{1/\gamma} R_s. \quad (1)$$

This kind of behavior is clearly observed in fractal point distributions. To illustrate it, we can use the fractal construction devised by Soneira & Peebles (1978). The model is built as follows: Inside a sphere of radius R , place randomly η spheres of radius R/λ ($\lambda > 1$). Within each of these spheres place again η spheres of radius R/λ^2 . The process is repeated L times and the last η^L centers are considered galaxies. A single clump is a simple fractal with a high degree of lacunarity, however Soneira & Peebles (1978) used a superposition of a number of these clumps in order to mimic the galaxy distribution provided by the Lick maps (Seldner et al. 1977). This construction has been recently taken by Peebles (1998) to show the extreme anisotropy of the distribution associated with this kind of fractal.

We have built a model that avoids overlapping of the spheres at each step. The parameters chosen are $\eta = 2, \lambda = 2, R = 60 \ h^{-1}\text{Mpc}$ and $L = 18$, which provides a dimensionality of $D_2 = 1$. In Figure 1 (upper left panel) we show the Aitoff projection of the model as seen by an observer situated at a point, close to the center of the simulation. The central left panel of Figure 1 shows the function $g(r) = 1 + \xi(r)$ for samples centered at this point and radius ranging from 0.1 to $10 \ h^{-1}\text{Mpc}$. We can see that, as a consequence of the fractal character of this model, $g(r)$ is very nearly a power-law. The figure also shows that the amplitude of $g(r)$ increases with the depth of the sample. The correlation length, r_0 , (shown in the bottom left panel of Figure 1) increases with sample size as is expected for a fractal (Pietronero 1987). Fractals are intrinsically rather anisotropic patterns, but we can use a superposition of these fractal clumps to increase the large-scale isotropy of

the model as Soneira & Peebles did to mimic the Lick catalog. The price we have to pay is to lose fractality at large scales, but since at small scales the fractal imprint of the model remains, the behavior of r_0 is still the one expected for a fractal as we can see in the right panels of Figure 1. At the upper right panel we show a realization of a superposition of 125 clumps with parameters $\eta = 2$, $\lambda = 1.76$, $R = 60 h^{-1}\text{Mpc}$, and L equals values taken from a Gaussian distribution with mean 6 and standard deviation 1. In this case overlapping is allowed. The two panels below show $g(r)$ and $R_0(R_s)$ for this specific model.

For the galaxy distribution, the increase of r_0 with the depth of the sample was already noticed in the first redshift survey analyzed so far, the CfA1 catalog (Einasto, Klypin, & Saar 1986). The issue, however, is more complicated because problems such as local inhomogeneities, corrections for Galactic extinction and, most important, luminosity segregation play an important role in the behavior of r_0 with sample depth (Davis et al. 1988; Martínez et al. 1993; Benoist et al. 1996; Willmer, da Costa, & Pellegrini 1998, Beisbart & Kerscher 2000).

The aim of this Letter is to see whether the correlation length increases with sample depth as expected in the fractal picture. We have studied the best available redshift catalogue for this purpose: the CfA2 survey (Geller & Huchra 1989; Huchra, Vogeley & Geller 1999). This sample is wide enough and deep enough to provide meaningful results. The strategy will be to disentangle the possible volume effect from the segregation of luminosity.

2. Description of the samples

We have worked on several volume-limited samples of the CfA2 surveys, constructed in the following way:

CfA2 north. First, we have extracted volume-limited samples as in Park et al. (1994). Radial velocities were transformed into comoving coordinate distances by means of Mattig’s formula (for $\Omega = 1$):

$$r(z) = \frac{2c}{H_0} \left(1 - \frac{1}{\sqrt{1+z}} \right), \quad (2)$$

with $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $c = 299792.5 \text{ km s}^{-1}$. The angular region is $8^{\text{h}} \leq \alpha \leq 16^{\text{h}}$ (note that in Park et al. (1994) the upper limit was 17^{h}) and $8.5^\circ \leq \delta \leq 44.5^\circ$. The names of the volume-limited samples listed in Table 1 are of the form CfAn*d*, where *d* is the rounded depth of the sample in $h^{-1}\text{Mpc}$. We list for each sample the number of galaxies N_g , the absolute magnitude limit M_ℓ , the depth R_{max} , the volume V , a typical length R_s associated with the sample (the cubic root of the volume), and finally the correlation length r_0 which has been fitted to that sample. Note that $M_\ell = 15.5 - 5 \log[r(z)(1+z)] - 25 - Kz$, where $K = 3$ is the appropriate value of the K -correction for the B filter and the term $+5 \log h$ has been systematically omitted in the values of the magnitudes throughout the paper.

In addition, we have drawn two more subsamples from CfAn101 having the same absolute magnitude limit but different geometry. First, we have extracted the galaxies contained in the maximum parallelepiped completely embedded within the boundaries of CfAn101 (see Figure 2, left panel). The resulting sample, BOXn, has 432 objects and a volume roughly 60% of the parent sample. Then we have calculated the depth that a sample with the same geometry as CfAn101 should reach in order to encompass the same volume as BOXn; this distance turned out to be $84.79h^{-1} \text{ Mpc}$. A subsample of CfAn101 containing only galaxies up to this distance is called CUTn (see Figure 2, central panel). Note that BOXn, CUTn and the volume-limited sample CfAn85 have all the same volume. In fact, CUTn is just a subsample of CfAn85 containing its brightest galaxies ($M < -19.70$).

CfA2 south. The samples extracted from the CfA2 south survey lie within the angular region $22.5^{\text{h}} \leq \alpha \leq 3^{\text{h}}$ and $0^\circ \leq \delta \leq 40^\circ$. In most of this region the Galactic extinction is low according to the maps of Burstein and Heiles (1982). Two volume-limited samples have been drawn from the survey, CfAs75 and CfAs59 (see Table 1) and from CfAs75 two subsamples have been extracted following the same procedure as in the north, BOXs and CUTs.

3. Results and discussion

For each sample the correlation function $\xi(r)$ has been calculated using the Rivolo estimator (Rivolo 1986),

$$\xi(r) = \frac{V}{N^2} \sum_{i=1}^N \frac{n_i(r)}{V_i} - 1, \quad (3)$$

where $n_i(r)$ is the number of galaxies lying at distance in the interval $[r - dr/2, r + dr/2]$ from galaxy i and V_i is the volume of the intersection of a shell with radii $r - dr/2$ and $r + dr/2$, centered at that galaxy, with the sample volume (logarithmic bins were used). Figure 3 (left panel) shows the results for all volume-limited samples extracted from the CfA north survey. We have performed a weighted least-squares fit of $\xi(r)$ in redshift space to a power-law $\xi(r) = (r_0/r)^\gamma$ within the range $[3 - 10 \ h^{-1}\text{Mpc}]$, where the fit is reasonably good. This is an important point to bear in mind, since different definitions of the clustering length are normally used in the literature and caution has to be exercised when intercomparing them (Peebles 1989). Poisson errors of the estimates of $\xi(r)$ have been used to weight the fit. By this means we have calculated a value of r_0 for each sample together with an error estimate. The results are reported in Table 1 and, for the volume-limited samples, in the right panel of Figure 3.

The most remarkable result is that the correlation length does not significantly change

with the depth of the sample. In any case, the linear increase predicted for a fractal pattern is clearly ruled out. For example, the volume of the sample CfAn101 is about three times the volume of the sample CfAn70, while the correlation length, r_0 , of both samples is comparable. Note that the plateau around $r_0 \simeq 6.7 h^{-1}\text{Mpc}$ observed in the right panel of Figure 3 includes also samples from the CfA2 south survey. In this case, we can stress that being the volume of the sample CfAs75 about twice the volume of the sample CfAs59, again the corresponding r_0 values are practically the same. It is interesting to note that when we have selected the largest parallelepiped embedded within CfAn101, i.e. BOXn, the value of the correlation length has increased although the volume has decreased nearly by half. Instead, the opposite behavior has been found in BOXs regarding its parent sample. Clearly the value of r_0 is more affected by the weight of local inhomogeneities within the sample volume than by the change in the volume itself.

As we have explained, CUTn is a subsample of CfAn85. Both samples lie within the same volume, but CUTn contains only galaxies brighter than the absolute magnitude limit of CfAn101 (-19.70). The intrinsically brighter subsample, CUTn, exhibits a larger value of the correlation length, $r_0 = 7.34 \pm 0.78 h^{-1}\text{Mpc}$, than the whole sample, CfAn85, for which $r_0 = 6.43 \pm 0.30 h^{-1}\text{Mpc}$. This effect is a fingerprint of the luminosity segregation and it is also observed in the CfA2 south samples, when we compare the value of r_0 corresponding to the sample CUTs, $r_0 = 7.54 \pm 0.63 h^{-1}\text{Mpc}$, with the value corresponding to the sample CfAs59, $r_0 = 6.34 \pm 0.28 h^{-1}\text{Mpc}$. The dependence of the correlation length on galaxy luminosity found by us is consistent with the results reported by Park et al. (1994), analyzing the amplitude of the power spectrum for the same survey.

Because of the effect of random peculiar motions, the correlation length in real space should be smaller by approximately $1 h^{-1}\text{Mpc}$ than the correlation length in redshift space (Peebles 1989, Loveday et al. 1995). Values of the redshift space correlation length near 6.5

$h^{-1}\text{Mpc}$ would therefore correspond to values $\sim 5.5 h^{-1}\text{Mpc}$ in real space (Davis & Peebles 1983).

In sum, we conclude that the correlation length calculated on volume-limited samples extracted from the CfA2 redshift survey is a rather stable quantity. In any case, the linear increase with radius of the sample predicted for a fractal is not observed. Our conclusions are reinforced by the fact that the correlation length in redshift space is still about $6 h^{-1}\text{Mpc}$ in redshift surveys that go much deeper than CfA2 (though they are sparser or narrower), like the Stromlo-APM, Las Campanas, and ESP redshift surveys (Loveday et al. 1995; Tucker et al. 1997; Guzzo et al. 2000). On still larger scales, Gladders & Yee (2000) have shown that the correlation length for luminous early-type galaxies does not change from $z = 0$ to $z = 1$, and Carlberg et al. (2000) find that the correlation amplitude declines slightly with redshift over the range 0.1 to 0.6 in the CNOC2 sample of very luminous galaxies.

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Table 1. Characteristics of the subsamples of the CfA2 catalogue

Sample	N_g	M_ℓ	R_{\max} ($h^{-1}\text{Mpc}$)	V ($h^{-1}\text{Mpc}$) ³	R_s ($h^{-1}\text{Mpc}$)	r_0 ($h^{-1}\text{Mpc}$)
CfA2 north						
CfAn101	905	-19.70	101.11	399160.64	73.63	6.88 ± 0.49
BOXn	432	-19.70	101.11	235390.79	61.74	8.04 ± 0.84
CUTn	444	-19.70	84.79	235390.79	61.74	7.34 ± 0.78
CfAn92	1074	-19.50	92.26	303242.65	67.18	7.19 ± 0.39
CfAn85	1134	-19.29	84.79	235390.79	61.74	6.43 ± 0.30
CfAn78	1159	-19.10	78.19	184608.80	56.94	6.88 ± 0.32
CfAn70	1113	-18.85	70.10	133041.53	51.05	6.65 ± 0.29
CfAn60	736	-18.49	59.95	83167.33	43.65	4.21 ± 0.31
CfA2 south						
CfAs75	722	-19.0	74.79	105598.94	47.27	6.61 ± 0.39
BOXs	435	-19.0	74.79	51705.30	37.25	5.70 ± 0.44
CUTs	427	-19.0	58.95	51705.30	37.25	7.54 ± 0.63
CfAs59	844	-18.46	58.95	51705.30	37.25	6.34 ± 0.28

Fig. 1.— *Left panels.* *Upper panel:* Equal–area projection of the Soneira-Peebles model as seen from an object near the center of the model. We have considered only the points lying within a spherical volume of radius $1/3$ of the radius of the first sphere. *Central panel:* The function $g(r)$ calculated on eight spherical samples of increasing radius in our fractal model. The values of the radii are shown in the legend. The reference line shows the expected slope for this fractal pattern. *Bottom panel:* Correlation length r_0 versus sample radius R_s . In the right panels, the same figures are displayed for a model having more large-scale isotropy, built by means of a superposition of 125 single fractal clumps similar to the one shown on the top left panel, although having different parameters (see text).

Fig. 2.— *Left panel:* The sample CfAn101 containing the parallelepiped which is the boundary of the subsample BOXn (galaxies within BOXn have been highlighted in red). *Central panel:* The same sample, but now the highlighted subsample is CUTn. *Right panel:* The sample CfAs75 containing the parallelepiped which is the boundary of the subsample BOXs (galaxies within BOXs have been highlighted in red).

Fig. 3.— *Left panel:* The correlation function for all the volume–limited samples drawn from the CfA2 north survey (CfAnd in Table 1). All of them are power laws with about the same amplitude, except for the closest sample CfAn60, which has a significantly smaller amplitude. Vertical dashed lines show the range where we have fitted a power–law to $\xi(r)$ to obtain the value of r_0 . *Right panel:* The value of the correlation length for all the volume–limited samples (CfAnd and CfAsd in Table 1). Again, apart from the small value for CfAn60, the rest of the samples yield values of r_0 lying within the range $[6.4 - 7.2 h^{-1}\text{Mpc}]$.





